Simulation of Colliding Solar Wind Streams

with Multifluid Codes

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(NASA-CR-138174) SIMULATION OF COLLIDING SOLAR WIND STREAMS WITH MULTIFLUID CODES (Maryland Univ.) ~~14~~ 15 p HC $4.00 CSCL 03B

N74-22429

Unclas

G3/29 37869

April 1974

Abstract

The description of a multifluid code with anomalous transport coefficients due to plasma instabilities self consistently followed in space and time is given. As an example we present simulations of colliding solar wind streamers. The results compare favorably with the observations.

I. Introduction

Anomalous transport due to plasma microinstabilities has long been known to be of extreme importance in understanding the observations of the solar wind plasma.[1] Most theoretical approaches have been directed towards the understanding of phenomena that can possibly be caused by instabilities or plasma processes[2] (ion heating, anomalous wave damping, etc.). Such analytic treatments can provide a rough estimate of the observations and may constitute a useful and necessary first step, but they will ultimately break down because many different plasma effects are acting at once and these effects are not evolving in a static spatially uniform plasma as is usually assumed in these approaches. The macroscopic properties and plasma microprocesses evolve together, feeding back into one another, and a self-consistent model is necessary if the highly non-linear interplay of the interactions is to be described properly.

An increased understanding of the non-linear theory of instabilities and recent developments in computational techniques at NRL have made it possible to develop codes that can perform such tasks. These have been applied successfully to C.T.R. and laboratory shock problems.[3] In this note we describe such a model, which has considerable flexibility for application to solar wind problems. As an example we shall simulate the interaction of colliding solar wind streams.

II. Model

The model consists of a set of multifluid equations, to be integrated numerically, which self-consistently include the effects of wave-particle interactions through anomalous transport terms. These terms depend on the instabilities present and evolve in time and space as the macroscopic plasma parameters evolve. Although two dimensional models are presently available at NRL, we restrict ourselves for simplicity to a 1D set of equations in Cartesian geometry. Each fluid (j) is characterized by its drift velocity u_j, its temperature T_j, and its density n_j which are functions of space and time. In addition, we follow the evolution of the magnetic field $\underline{B}$ and the electric field $\underline{E}$. The coupled set of equations can be written:

$$\frac{\partial}{\partial t} n_j = - \frac{\partial}{\partial x} (n_j u_j) \tag{1}$$

$$\frac{\partial}{\partial t} (n_j u_j) = - \frac{\partial}{\partial x} (n_j u_j{}^2) + Z_j \frac{e u_j}{m_j} \left(\underline{E} + \frac{u_j \times \underline{B}}{c} \right) - \frac{K_B}{m_j} \frac{\partial}{\partial x} (n_j T_j) - n_j \sum_\alpha \nu_{j\alpha} (u_\alpha - u_j) - \left(\frac{\partial n_j u_j}{\partial t} \right)_A \tag{2}$$

$$\frac{\partial}{\partial t} T_j = - \frac{\partial}{\partial x} (u_j T_j) - (\gamma-2) T_j \frac{\partial}{\partial x} u_j + \left(\frac{\gamma-1}{K_B} \right) \sum_\alpha \nu_{ja} (u_\alpha - u_j)^2 + \sum_\alpha \frac{T_\alpha - T_j}{\tau_{\alpha j}} - \begin{matrix} \text{Radiation Losses,} \\ \text{External Sources,} \\ \text{Thermal Conduction,} \\ \text{Etc.} \end{matrix} - \left(\frac{\partial T_j}{\partial t} \right)_A \tag{3}$$

$$\underline{v}_e = - \frac{c}{4\pi e \, n_e} \nabla \times \underline{B} + \frac{1}{n_e} \sum_j n_j Z_j u_j \tag{4}$$

$$\underline{E} = - \frac{1}{c} (v_e \times \underline{B}) - \frac{K_B}{e n_e} \nabla (n_e T_e) - \frac{m_e}{e} \sum_j \nu_{ej} (u_j - v_e) \tag{5}$$

$$n_e = \sum_j n_j Z_j \tag{6}$$

$$\frac{\partial \underline{B}}{\partial t} = - c \; (\nabla \times \underline{E}) \tag{7}$$

$$\nu_{j\alpha} = \nu_{j\alpha} (\underline{B}, n_\alpha, T_\alpha, u_\alpha, n_j, T_j, u_j) \tag{8}$$

Without the terms $\left[\frac{\partial n_j u_j}{\partial t}\right]_A$ and $\left[\frac{\partial T_j}{\partial t}\right]_A$, equations (1-8) are simply a multifluid description of the system coupled collisionally via $\nu_{j\alpha}$, $\tau_{j\alpha}$ given by the usual Spitzer values. In equation (3) one can insert any sources or sinks of energy the particular model may require, as well as thermal conduction. The terms $\left[\frac{\partial n_j u_j}{\partial t}\right]_A$, $\left[\frac{\partial T_i}{\partial t}\right]_A$ represent the effects of anomalous (collective) processes and the prescription employed in the code should be derived from independent non-linear calculations. We have performed such work for situations where electrons and various ion species stream through each other. The results have been reported in Ref. 4. In this code we have included effects of the magnetized ion-ion two stream instability, the modified two-stream instability and the beam cyclotron instability. For these instabilities, the momentum transfer terms take the form

$$\left[\frac{\partial n_i u_i}{\partial t}\right]_{\text{Ion Ion}} \sim 0.1\, \Omega_H\, n_i \frac{\rho_j}{\rho_T} (v_j - v_i)\, F_1 (\rho_i/\rho_j)$$

$$\left[\frac{\partial n_i u_i}{\partial t}\right]_{\substack{\text{Modified}\\ \text{Two Stream}}} \sim 0.1\,\Omega_H\, n_i \left(1-\frac{n_i}{n_e}\right)(v_e - v_i)$$

$$\left[\frac{\partial n_i u_i}{\partial t}\right]_{\substack{\text{Beam}\\ \text{Cyclotron}}} \sim 0.02\,\omega_{pe}\,\frac{n_i^{\,2}}{n_e}\left(1-\frac{n_i}{n_e}\right)\frac{m_e}{m_i}\,(v_e - v_i)$$

and the heating terms take the form:

$$\left[\frac{\partial T_i}{\partial t}\right]_{\text{Ion Ion}} \sim 0.1\,\Omega_H\left(\frac{\gamma-1}{K_B}\right)\frac{\rho_j}{\rho_T}\,(v_i - v_j)^2\, m_i\, F_2(\rho_i/\rho_j)$$

$$\left[\frac{\partial T_i}{\partial t}\right]_{\substack{\text{Modified}\\ \text{Two Stream}}} \sim 0.1\,\Omega_H\left(\frac{\gamma-1}{K_B}\right)\frac{m_i}{2}\left(\frac{n_i}{n_e}\right)^{\frac{1}{3}}(v_i - v_e)^2$$

$$\left[\frac{\partial T_e}{\partial t}\right]_{\substack{\text{Modified}\\ \text{Two Stream}}} \sim 0.1\,\Omega_H\left(\frac{\gamma-1}{K_B}\right) m_i\,(\rho_i/\rho_T)^{\frac{1}{3}}\cdot\left\{1-\frac{1}{2}\left(\frac{n_i}{n_e}\right)^{\frac{1}{3}}\right\}\cdot(v_i - v_e)^2$$

$$\left[\frac{\partial T_i}{\partial t}\right]_{\substack{\text{Beam}\\ \text{Cyclotron}}} \sim 0.02\,\omega_{pe}\left(\frac{\gamma-1}{K_B}\right) m_e\,\frac{n_i}{n_e}\,|v_i - v_e|\left\{\frac{K_B T_e}{m_i}\;\frac{n_i}{n_e}\right\}^{\frac{1}{2}}$$

$$\left[\frac{\partial T_e}{\partial t}\right]_{\substack{\text{Beam}\\ \text{Cyclotron}}} \simeq 0.02\,\omega_{pe}\left(\frac{\gamma-1}{K_B}\right) m_e\,\frac{n_i^{\,2}}{n_e^{\,2}}\,|v_i - v_e|\left(|v_i - v_e| - \left\{\frac{K_B T_e}{m_i}\;\frac{n_i}{n_e}\right\}^{\frac{1}{2}}\right)$$

where the subscript i refers to the ith ion species, j to the jth ion species and e to the electrons. ρ_T is the total mass density, Ω_H the lower hybrid frequency, ω_{pe} is the electron plasma frequency, and F_1 and $F_2(\rho_i/\rho_j)$ are factors of order unity.

These instabilities operate when local conditions are favorable. The criteria for these instabilities are as follows:

$$\left.\begin{array}{l} (v_i - v_j)^2 \lesssim \dfrac{12.5}{\rho_T}\left(\dfrac{B^2}{8\pi} + n_e K_B T_e\right) \\[2ex] \dfrac{k_B T_i}{m_i} \ \underline{\text{And}} \ \dfrac{k_B T_j}{m_j} \lesssim (v_i - v_j)^2 \end{array}\right\} \text{Ion-Ion Instability}$$

$$\left.\begin{array}{l} (v_i - v_e)^2 \lesssim \dfrac{2}{\rho_T}\left(\dfrac{B^2}{8\pi} + n_e K_B T_e\right) \\[2ex] \dfrac{k_B T_i}{m_i} \lesssim (v_i - v_e)^2 \end{array}\right\} \text{Modified Two-Stream}$$

$$\left.\begin{array}{l} \dfrac{k_B T_e}{m_i}\,\dfrac{n_i}{n_e} \lesssim (v_i - v_e)^2 \\[2ex] T_e \dfrac{n_i}{n_e} > 6.25\, T_i \end{array}\right\} \text{Beam Cyclotron}$$

Most of the ion heating in the simulations to be described will be due to the ion-ion instability.

III. Macrostructure of Colliding Streamers

Using the above model, we proceeded to simulate the regions in the interplanetary plasma where fast plasma streams collide with slower ones.[5] We employed a three fluid model, one fluid representing the fast streaming ions, one the slow ions, and one the electrons. The simulation was performed in the reference frame of the slower moving plasma, and the initial configuration is shown in Figure 1. Figures 2 and 3 show the subsequent evolution in time and space, and the agreement with reported measurements is remarkable. In order to demonstrate the effects of the anomalous terms, we equated them to zero in an otherwise identical simulation, and the results, shown in Figure 4, and are in total disagreement with the observed ion heating. The densities, velocities and temperatures plotted in Figures 1-4 are total quantities, summed over both ion species.

In order to demonstrate the mass-dependent differential ion heating caused by the instabilities, we performed simulations with proton and alpha particle "fast" streams interacting with a proton background. Temperatures of the individual species are shown in Figure 5 for the proton-proton case, and in Figure 6 for the alpha-proton case. In agreement with measurements, $T_\alpha/T_p \sim 4$.

IV. Microstructure after the Interaction

The multifluid approach, while it provides a measure of the thermalization and of the relative streaming and thermal energies, cannot give a description of the velocity distribution function. However, since we can find the dominant thermalization mechanism from the multifluid calculation, we can proceed to simulate that particular instability in a particle code[6] to find the ion velocity distribution function after thermalization. Figure 7 shows the ion distribution before and after thermalization. In the latter case, the distribution function is similar to the one measured by Feldman.[7] One should note that this distribution is no longer unstable, but is marginally stable, and will persist over a collisional time scale, the ions streaming down the field lines in a one-fluid fashion. What Feldman sees is the result of a short wavelength ($kR_i \ll 1$) instability which occurred at the colliding streamer region and subsequently drifted away.

Conclusions

We believe that the multifluid approach outlined here is, at this time, the most powerful tool with which a comparison of the observations of the solar wind plasma and the various theories can be accomplished. The model is flexible enough such that any additional processes relevant to the particular problem can be incorporated. The example which we presented shows clearly how a combination of multifluid and particle codes can explain most of the features observed in colliding solar wind streamers, and it demonstrates how erroneous conclusions will be drawn if the plasma processes are neglected.

Acknowledgement

The work of one of us (K. Papadopoulos) was supported by NASA grant NGL 21-007-005.

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Figure Captions

Fig. 1: Magnetic field profiles and total ion temperature, velocity and density profiles at t = 0. Background streamer partly interpenetrated by "fast" streamer. A sharp initial density cutoff is assumed for the "fast" streamer. An initial ion temperature of 1 ev. is assumed.

Fig. 2: Profiles at t = 10 seconds, for the case with plasma instabilities operative.

Fig. 3: Profiles at t = 20 seconds, for the case with plasma instabilities operative.

Fig. 4: Profiles at t = 20 seconds, for the case with plasma instabilities turned off. Ion heating results from simple adiabatic compression.

Fig. 5: Temperature profiles for the individual ion streams and for the electrons at t = 5 seconds. Here a "fast" streamer consisting of protons counterstreams with a proton background.

Fig. 6: Temperature profiles at t = 5 seconds, for a "fast" alpha-particle streamer counterstreaming with a proton background.

Fig. 7: Ion velocity distribution functions before and after thermalization via the magnetized ion-ion two stream instability.

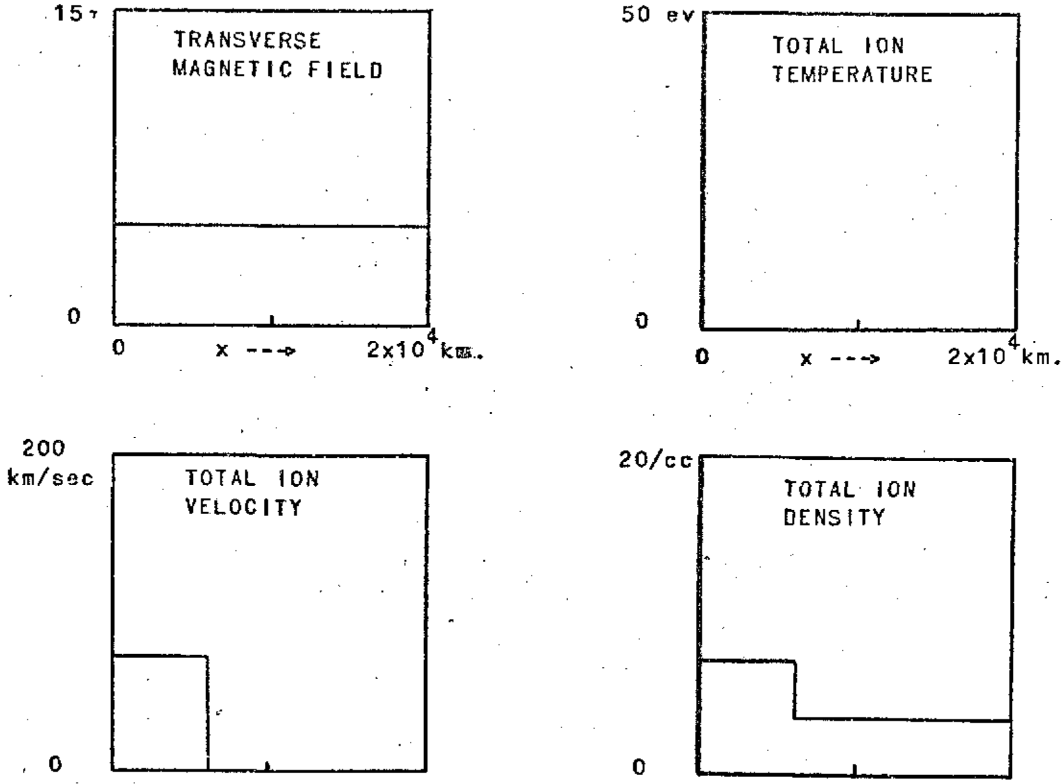


Figure 1. Initial configuration.

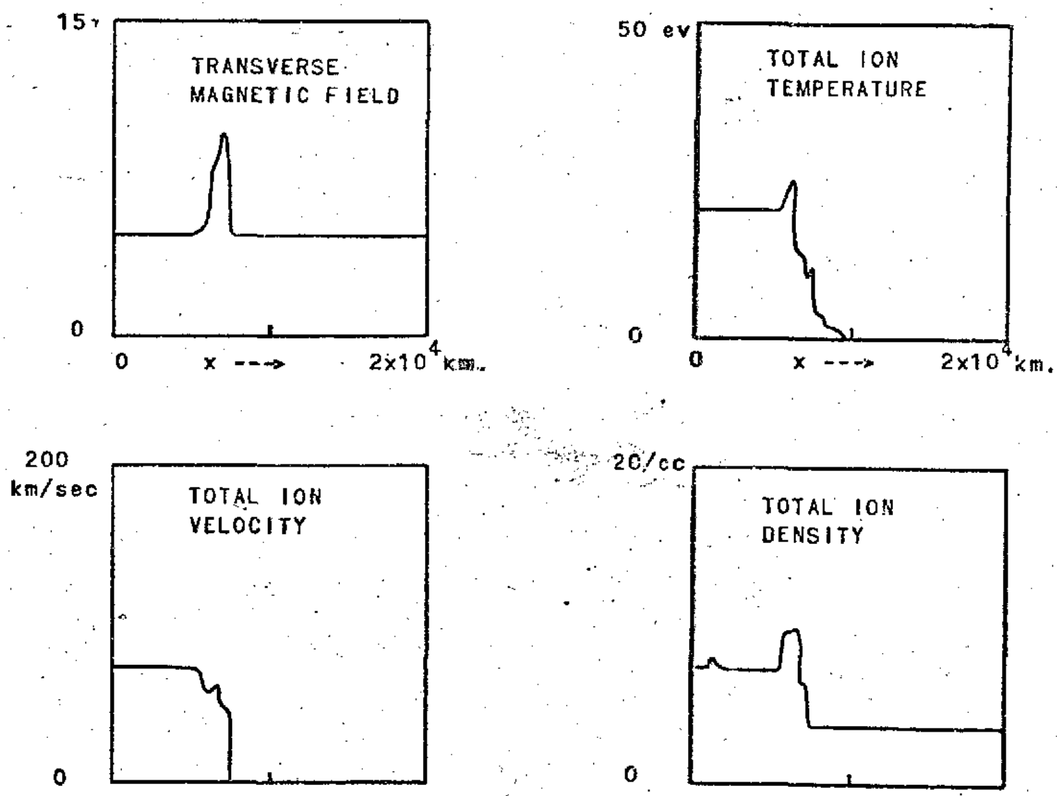


Figure 2. With instabilities. t = 10 sec.

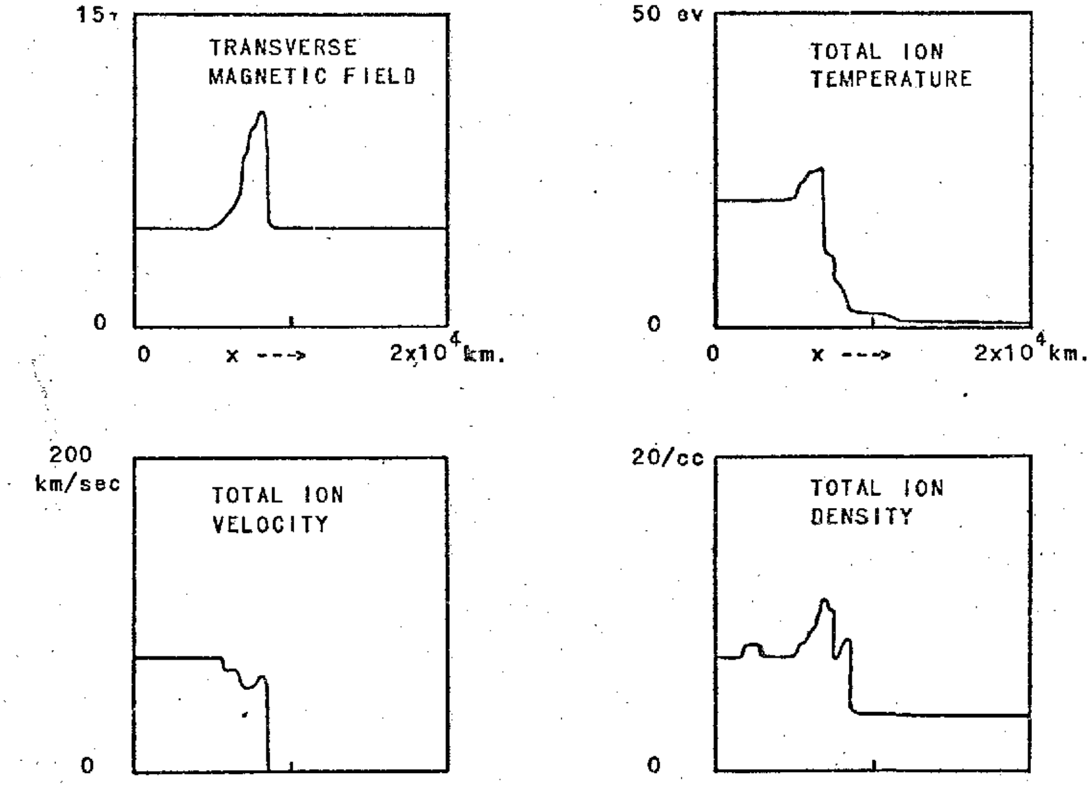


Figure 3. With instabilities. t = 20 sec.

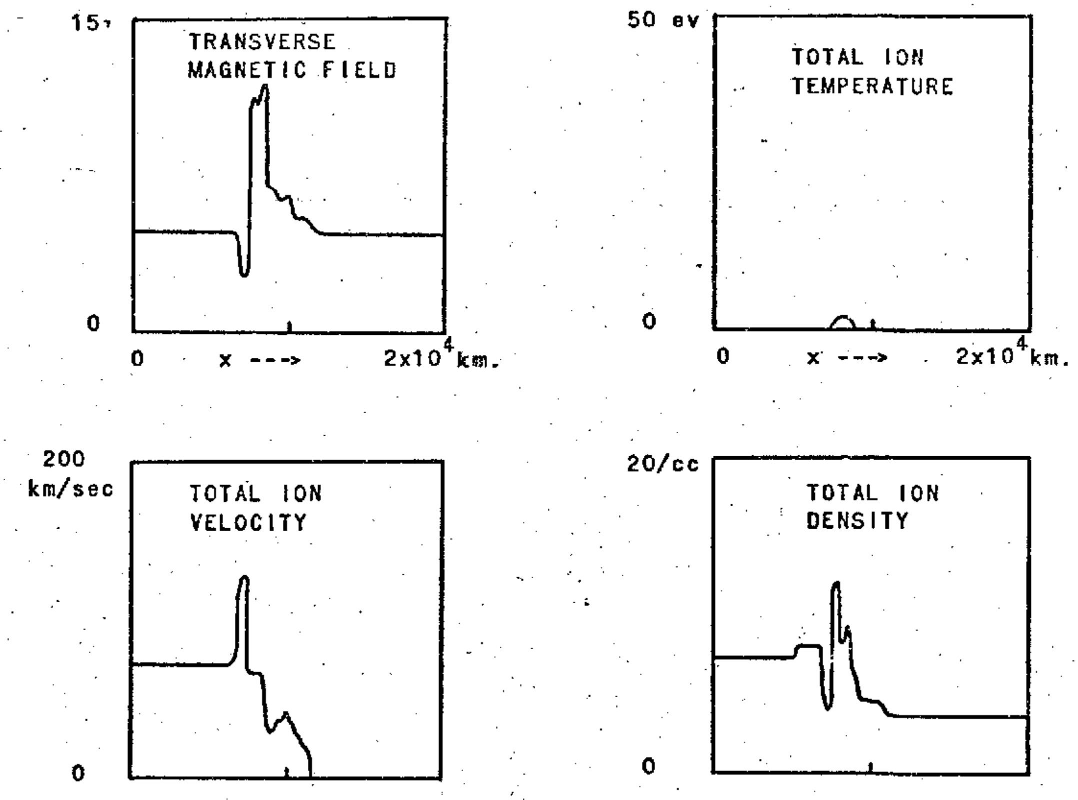


Figure 4. Laminar case. t = 20 sec.

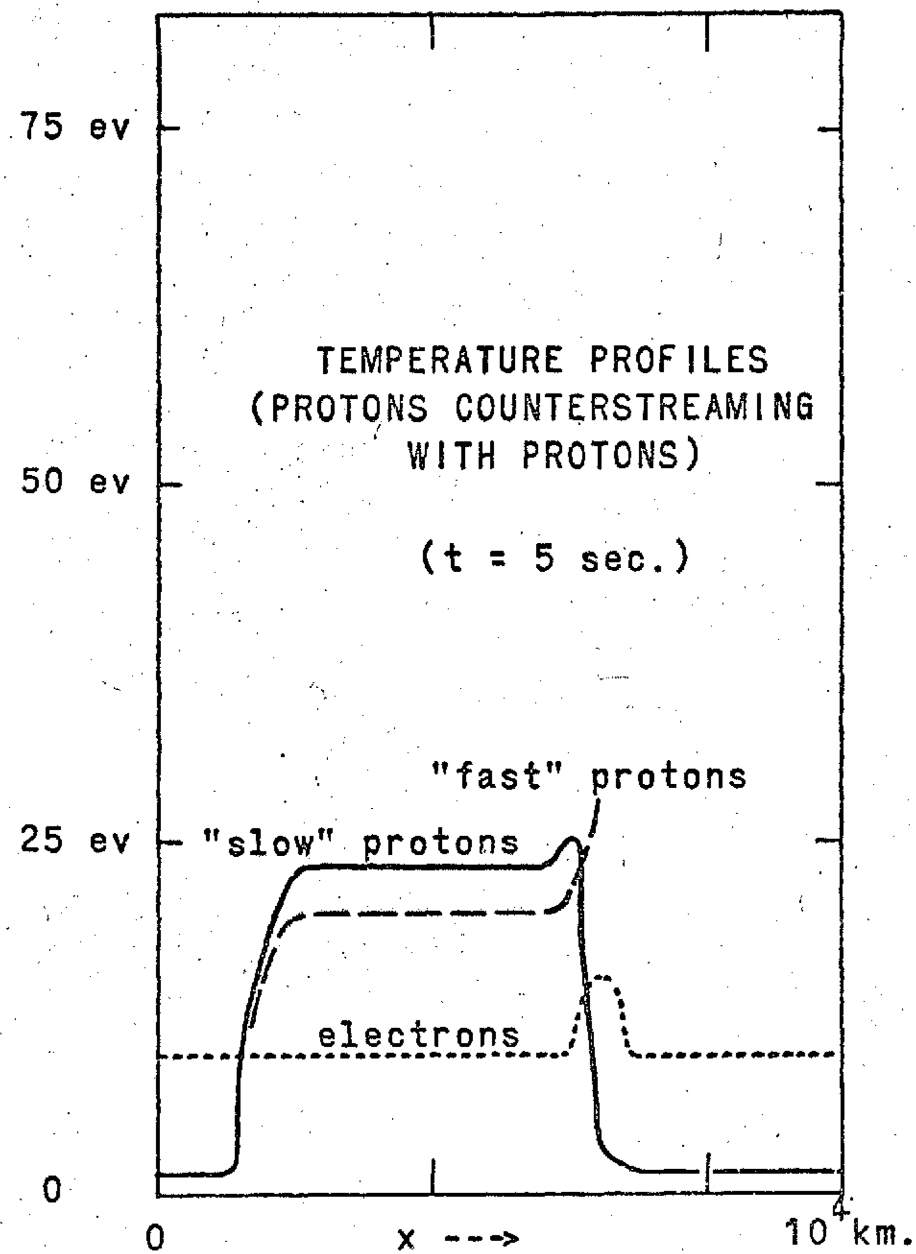


Figure 5. Temperature profiles.

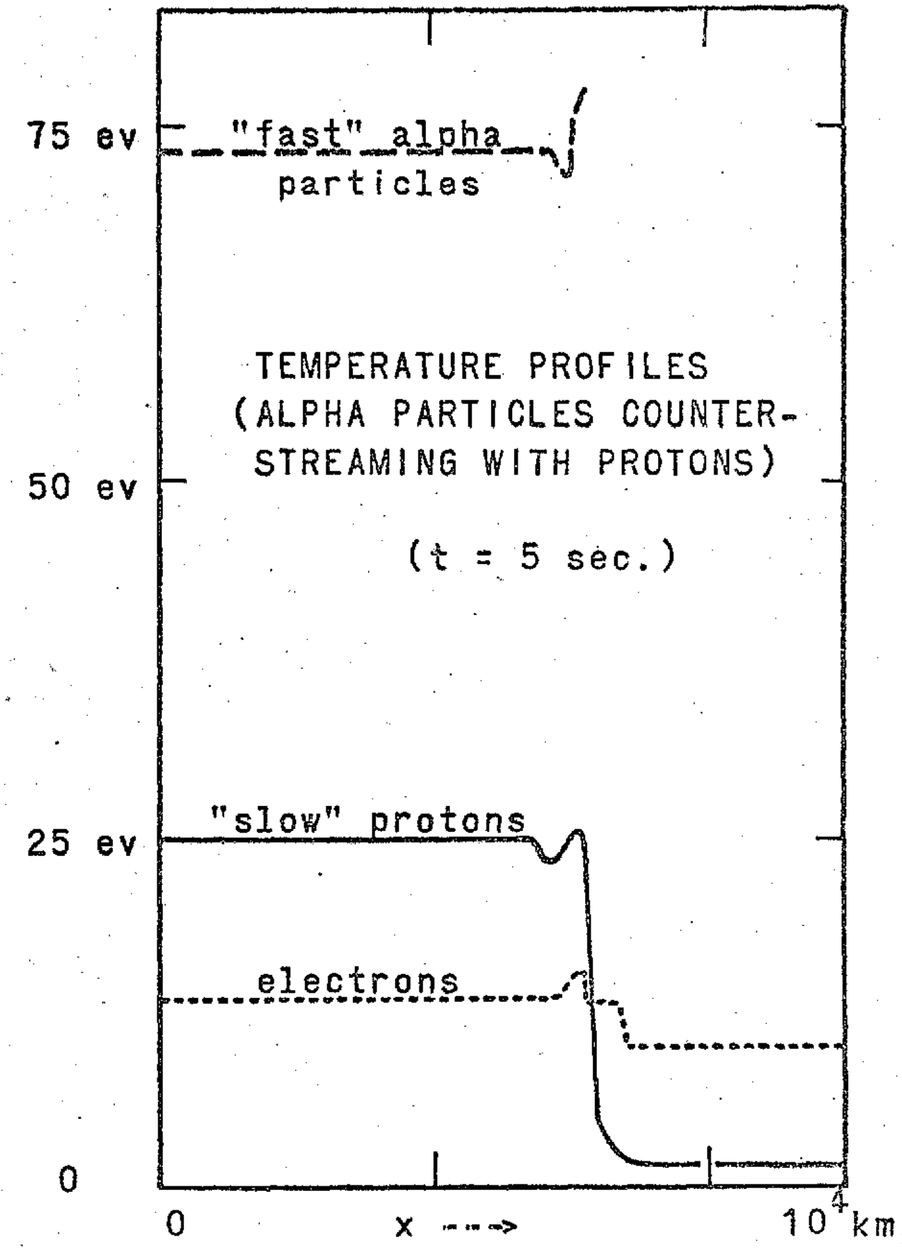
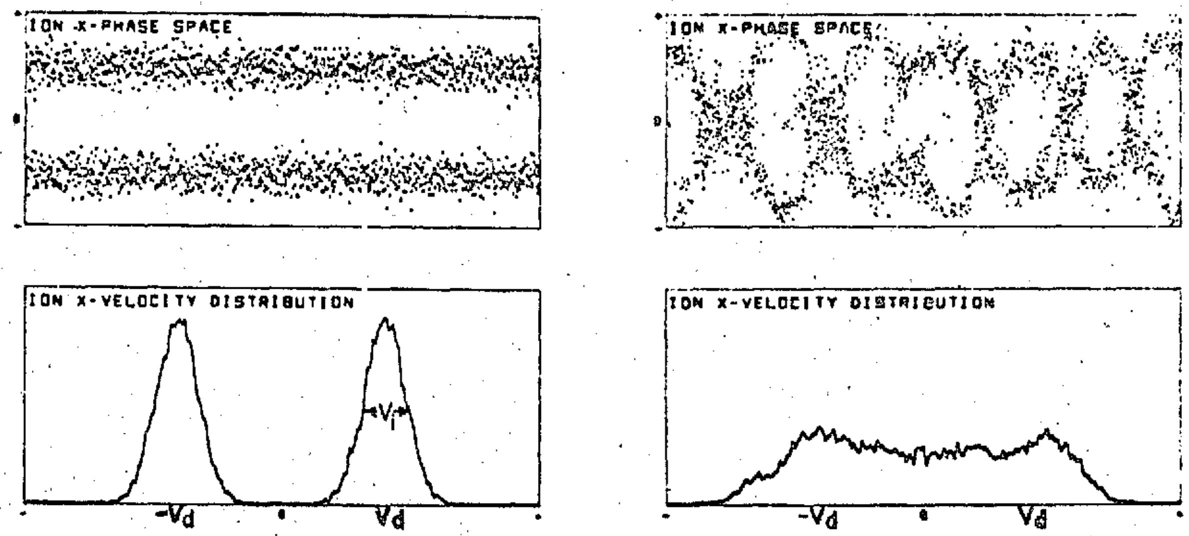


Figure 6. Temperature profiles.



(a) initial configuration.

(b) final configuration.

Figure 7. Ion velocity distribution functions.